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Structure Function Scaling of a 2MASS Extinction Map of Taurus.

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ABSTRACT

We compute the structure function scaling of a 2MASS extinction map of the Taurus molecular cloud complex. The scaling exponents of the structure functions of the extinction map follow the Boldyrev's velocity structure function scaling of super–sonic turbulence. This confirms our previous result based on a spectral map of ^{13}CO J=1-0 covering the same region and suggests that super-sonic turbulence is important in the fragmentation of this star–forming cloud.

Subject headings: turbulence – ISM: dust, extinction – ISM: kinematics and dynamics

1. Introduction

Stars are formed predominantly from very large clouds of cold interstellar gas containing up to millions of solar masses of material. The dynamics of such clouds is therefore a crucial ingredient in the process of star formation. Observations of emission spectra of molecular transitions have shown that the kinematics of star–forming clouds is best described as supersonic random motions, often referred to as supersonic turbulence. Numerical simulations of supersonic turbulence have indeed been compared successfully with the observations, in the sense that many statistical properties of numerical supersonic turbulent flows are also found in the observational data (e.g. Padoan et al. 1998, 1999, 2001).

The cold gas in star–forming clouds, especially their molecular component, cools very rapidly down to a typical equilibrium temperature of approximately 10 K. The shocks caused by the observed random supersonic velocity field are therefore roughly isothermal, which allows them to compress the gas effectively. Expansions are also favored by the isothermal behavior of the gas and large voids of very low density can be generated. The result is

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a very large contrast between the highest and the lowest densities, as commonly found in numerical simulations with an isothermal equation of state. We usually refer to this effect of the turbulent velocity on the density field as *turbulent fragmentation*, to stress the fact that star–forming clouds are more likely fragmented into dense prestellar cores directly by the turbulent velocity field, rather than by a hierarchical process of gravitational fragmentation.

The traditional way to study the dynamics of star forming clouds is to probe their kinematics by the Doppler shift in spectral lines of molecular transitions. However, the dynamics can also be studied through the density field, as the gas density is so strongly affected by the supersonic velocity. The investigation of the cloud spatial structure may be used to test predictions of numerical and analytical models more directly than using the velocity field. Projected density is in fact easier to measure than the velocity field. This is especially true if stellar extinction measurements are available, since they provide the most reliable estimate of column density.

Thanks to the recently completed "Two Micron All Sky Survey" (2MASS; Cutri et al. 2001), it is now possible to generate extinction maps of several extended giant molecular cloud complexes with a dynamical range in both column density and spatial resolution that is not matched by any molecular line survey. In this work we derive new extinction maps of the Taurus region using 2MASS point source data, and show that we can probe values of dust column density over more than two orders of magnitude and achieve a spatial resolution higher than in IRAS 100 μm images (§ 2). In § 3 we present the results of the structure function analysis of the extinction map and obtain a scaling that is indistinguishable from that of the velocity structure functions in supersonic turbulence. Conclusions are drawn in § 4.

2. Extinction Maps from 2MASS Data

Lada et al. (1994) use the stellar extinction determined from the IR color excess, instead of stellar counts, to map interstellar clouds. Their method is based on superimposing a regular grid on the observed region, and giving each grid cell a value of extinction equal to the average extinction of the stars within that cell. The number of stars per cell decreases with increasing average extinction in the cell, because only the brightest background stars can be seen through a large column of dust. The method has been improved by Lombardi & Alves (2001), using Gaussian filtering to obtain a smooth regularly sampled map.

In this work we compute stellar extinction maps with the method proposed by Cambresy et al. (2002). This method uses adaptive cells that contain a fixed number of stars instead of cells of fixed size. In this way it is possible to keep the spatial resolution as high as allowed by the local stellar density. The spatial resolution is higher in regions of low extinction than in regions of large extinction, where fewer background stars are detected and larger cells must be used. The average spatial resolution over the whole map can be changed by changing the number of stars per cell.

The color excess is computed using the relation $E_{H-K_s} = (H - K_s)_{\rm obs} - (H - K_s)_{\rm int}$, where $(H - K_s)_{\rm obs}$ is the observed median color in a cell and $(H - K_s)_{\rm int}$ is the intrinsic median color, estimated from the colors of supposedly unreddened stars. In the method by Lada et al. (1994) the mean color is used instead of the median color. We prefer to use the median color because it has the advantage of minimizing the effect of foreground stars, as shown by Cambresy et al. (2002). Visual extinction values are obtained from the color excess using the Rieke and Lebofsky (1985) extinction law, which results in the relation $A_V = 15.87 \times E_{H-K_s}$.

Cambresy et al. (2002) have applied this method to study the North America and Pelican Nebulae. However, these nebulae are rather close to the galactic plane, and are therefore very difficult to study with extinction measurements due to the mixture of stars and other clouds in their background. The Taurus molecular cloud complex is far from the galactic plane (approximately 15° south) and very close to us, at a distance of approximately 140 pc (Kenyon, Dobrzycka & Hartmann 1994). Contamination from foreground stars is therefore negligible for this region, as well as confusion with other clouds in the distant background.

We have computed extinction maps of the Taurus molecular cloud complex using 1, 3, 10, 30 and 100 stars per cell covering a region of $12° \times 10°$. Figure 1 shows the map obtained with 10 stars per cell. Approximately 115 known young embedded stars (Herbig & Bell 1988; Leinert et al. 1993; Kenyon et al. 1994; Briceno et al. 1998) have been excluded from the 2MASS catalog before computing the extinction maps. The intrinsic color is computed as the median color of stars in regions where no ^{12}CO (Dame et al. 2001) is detected, within a field larger than the actual extinction map ($155° < l < 177°$) and is found to be $(H - K_s)_{\rm int} = 0.13$ mag. The standard deviation of the color of these unreddened stars provides an estimate of the uncertainty (1-σ noise) in the extinction maps.

The value of this uncertainty, the median angular resolution (cell diameter) and the maximum extinction value for each map are given in Table 1. Since cell sizes are adapted to contain a fixed number of stars, the statistical uncertainty is independent of the extinction level (the noise is uniform over the map). The highest resolution achieved with these maps is remarkable. The map with 3 stars per cell, for example, yields a median resolution of 1.7', almost 3 times better than the resolution of IRAS 100 μm images (4'×5').

As shown in Table 1, we can probe values of A_V ranging from 0.3 mag (1σ detection in the 100 stars per cell map) to 33 mag (largest extinction in the 1 star per cell map). Using a standard gas to dust ratio, $N(H+H_2)/A_{\rm V} = 2\times10^{21}$ cm^{-2}mag^{-1} (Bohlin et al. 1978), the range in extinction corresponds to approximately two orders of magnitude in column density, from $N(H+H_2) = 6\times10^{20}$ cm^{-2} to $N(H+H_2) = 6.6\times10^{22}$ cm^{-2}.

3. Structure Functions of Projected Density

The structure functions of the extinction map, $A_V(\mathbf{x})$, are defined as:

$$S_p(l) = \langle |A_V(\mathbf{x}) - A_V(\mathbf{x}+\mathbf{l})|^p \rangle \tag{1}$$

where p is the order and the average is extended to all map positions $\mathbf{x}$. In turbulent flows it is found that the structure functions of velocity are power laws. Assuming that the structure functions of projected density (or extinction) are power laws as well, we call $\eta(p)$ the exponents of these power laws:

$$S_p(l) \propto l^{\eta(p)} \tag{2}$$

In Figure 2 we have plotted the structure functions of the map obtained with 10 stars per cell, relative to the third order structure function, since we are interested in investigating the relative scaling, $\eta(p)/\eta(3)$ (this follows the idea of extended self–similarity by Benzi et al. 1993 and Dubrulle 1994).

The function $\eta(p)/\eta(3)$ is plotted in Figure 3. The velocity scaling predicted by Boldyrev (2002) for supersonic turbulence is shown as a solid line, the one predicted by She & Leveque (1994) for incompressible turbulence is plotted as a dashed line and the Kolmogorov's velocity scaling, $p/3$, is shown by the dotted line. The scaling of the structure functions of projected density is found to be the same as the scaling of velocity structure functions in supersonic turbulence. *A priori* we do not know if the relative scaling of projected density should be the same as that of the velocity; the velocity scaling from theoretical models is shown here only as a reference.

Padoan et al. (2002) have recently analyzed in a similar way ^{13}CO maps of the same Taurus region and of Perseus. The present result for the relative scaling of the structure functions in Taurus confirms the results of that work. However, the sample size from the 2MASS data is much larger than the sample size of the ^{13}CO map. Furthermore, the spatial resolution of the extinction map is slightly better and the range of column density sampled 20 times larger than in the ^{13}CO map. The statistical significance of high order moments from the analysis of the 2MASS data should therefore be much higher than from the ^{13}CO maps.

4. Conclusions

Boldyrev (2002) has recently proposed an analytic model for the velocity structure function scaling in supersonic turbulence. The model is an extension of the scaling of incompressible turbulence proposed by She & Leveque (1994) and has already been successfully tested with numerical simulations of supersonic turbulence (Boldyrev, Nordlund & Padoan 2002a). An equivalent analytic model for the scaling of the structure functions of projected density in supersonic turbulence is not available yet. Only the slope of the second order structure function has been derived from the velocity structure functions, under certain approximations (Boldyrev, Nordlund & Padoan 2002b). However, the fact that the projected density follows the same scaling as the velocity field in supersonic turbulence suggests that the density field in the Taurus region is the result of a multiplicative process with a Log-Poisson statistics (Dubrulle 1994), very likely the result of the turbulent fragmentation.

The importance of supersonic turbulence in the fragmentation of star-forming regions has been established in previous works (e.g. Padoan & Nordlund 1999; Padoan et al. 2001; Padoan & Nordlund 2002). The purpose of the present work is primarily to determine the statistical properties of the fragmentation process, independent of its origin. Such statistical properties may be universal, for example if they are mainly the consequence of turbulence, or depend on several physical parameters, such as gas density, temperature, turbulent velocity dispersion and star formation activity. We plan to compute and analyze 2MASS extinction maps of different extended star-forming regions in order to establish the properties of the fragmentation process that leads to the formation of stars in different environments.

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REFERENCES

Benzi, R., Ciliberto, S., Tripiccione, R., Baudet, C., Massaioli, F., & Succi, S. 1993, Phys. Rev. E, 48, 29

Boldyrev, S. 2002, ApJ, 569, 841

Boldyrev, S., Nordlund, Å., & Padoan, P. 2002a, Physical Review Letters, in press (see also astro-ph/0203452)

—. 2002b, ApJ, 573, 678

Briceño, C. ., Hartmann, L., Stauffer, J., & Martín, E. 1998, AJ, 115, 2074

Cambrésy, L., Beichman, C. A., Jarrett, T. H., & Cutri, R. M. 2002, AJ, 123, 2559

Dubrulle, B. 1994, Phys. Rev. Lett., 73, 959

Herbig, G. H. & Bell, K. R. 1988, Catalog of emission line stars of the orion population : 3 : 1988 (Lick Observatory Bulletin, Santa Cruz: Lick Observatory, —c1988)

Kenyon, S. J., Dobrzycka, D., & Hartmann, L. 1994, AJ, 108, 1872

Kolmogorov, A. N. 1941, Dokl. Akad. Nauk. SSSR, 30, 301

Lada, C. J., Lada, E. A., Clemens, D. P., & Bally, J. 1994, ApJ, 429, 694

Leinert, C., Zinnecker, H., Weitzel, N., Christou, J., Ridgway, S. T., Jameson, R., Haas, M., & Lenzen, R. 1993, A&A, 278, 129

Lombardi, M. & Alves, J. 2001, A&A, 377, 1023

Padoan, P., Bally, J., Billawala, Y., Juvela, M., & Nordlund, Å. 1999, ApJ, 525, 318

Padoan, P., Boldyrev, S., Langer, W., & Nordlund, Å. 2002, in preparation

Padoan, P., Juvela, M., Bally, J., & Nordlund, Å. 1998, ApJ, 504, 300

Padoan, P., Juvela, M., Goodman, A. A., & Nordlund, Å. 2001, ApJ, 553, 227

Padoan, P. & Nordlund, Å. 1999, ApJ, 526, 279

Padoan, P. & Nordlund, Å. 2002, ApJ, in press (see also astro-ph/0011465)

Rieke, G. H. & Lebofsky, M. J. 1985, ApJ, 288, 618

She, Z.-S. & Lévêque, E. 1994, Phys. Rev. Lett., 72, 336

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Table and Figure captions:

Table 1: Extinction map parameters for different spatial resolutions.

Figure 1: Extinction map of the Taurus region computed with 10 stars per cell.

Figure 2: Structure functions of the extinction map from $p = 1$ to 20 relative to the third order structure function. The extinction map with 10 stars per cell has been used. The solid lines show the least square fits used to define the power law slopes.

Figure 3: Top panel: Relative structure function scaling. Bottom panel: Structure function exponents divided by the Boldyrev's scaling.

No. of stars	σ_{A_V} (mag)	Median Resolution (arcmin)	$A_{V,\mathrm{max}}$ (mag)
100	0.26	12.4	8.0
30	0.34	6.7	11.7
10	0.49	3.4	19.5
3	0.85	1.7	26.3
1	1.30	1.0	32.7

Table 1: Extinction map parameters for different spatial resolutions

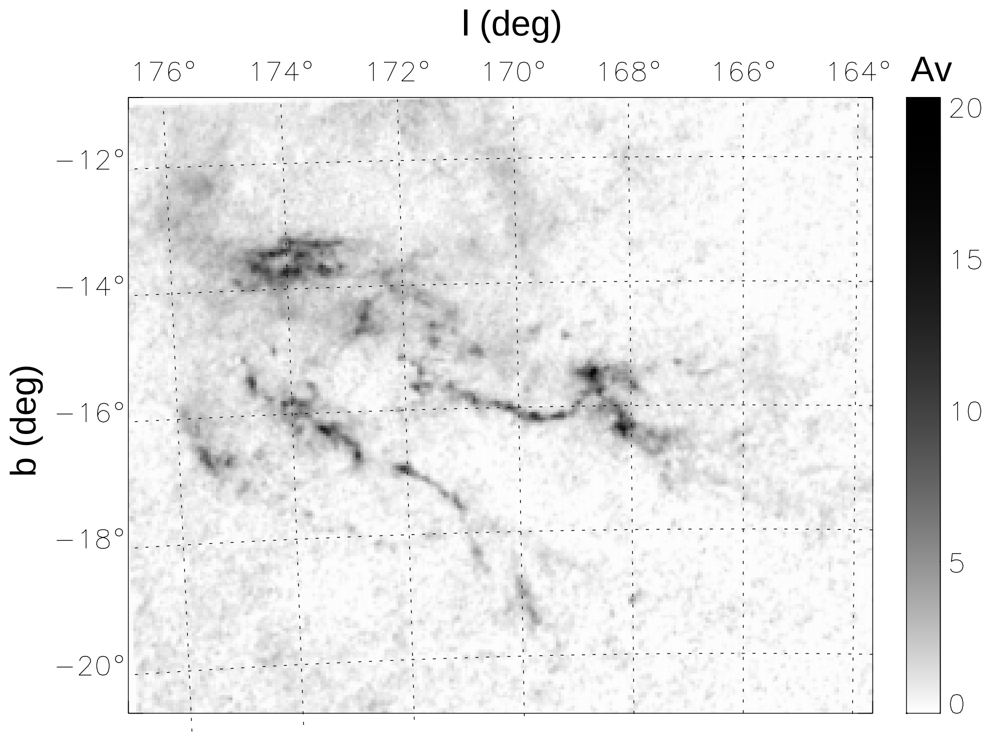

Fig. 1.—

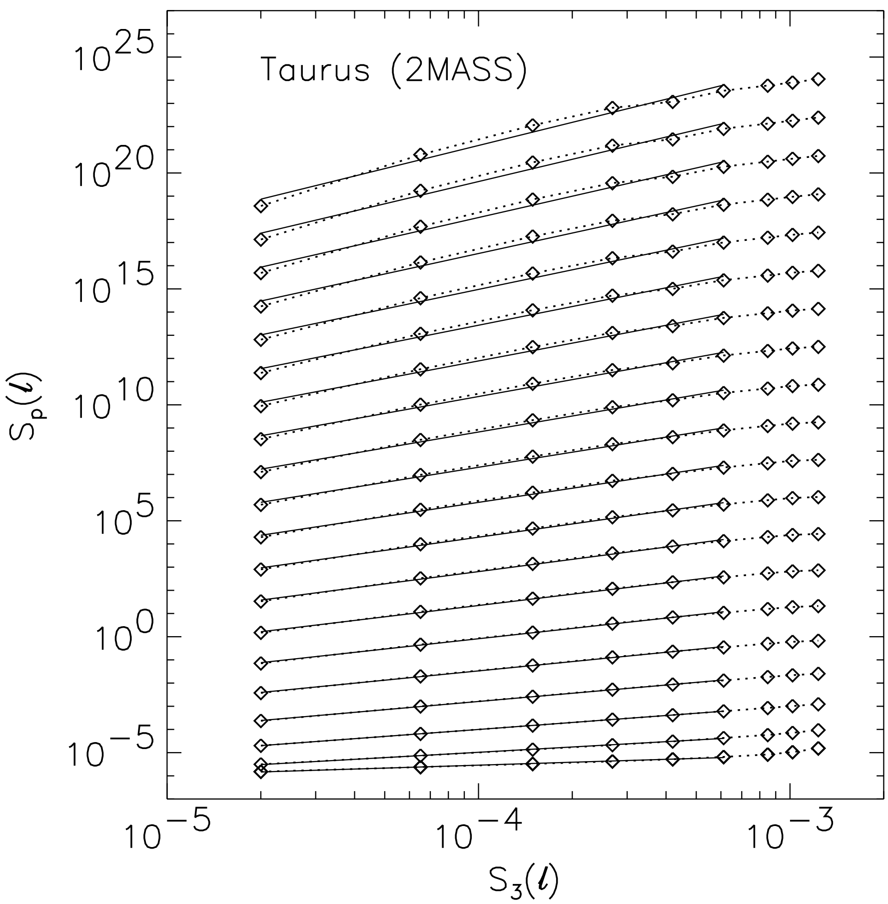
Taurus (2MASS)
10^{25}
10^{20}
10^{15}
10^{10}
10^{5}
10^{0}
10^{-5}
$S_p(\ell)$
10^{-5}
10^{-4}
10^{-3}
$S_3(\ell)$

Fig. 2.—

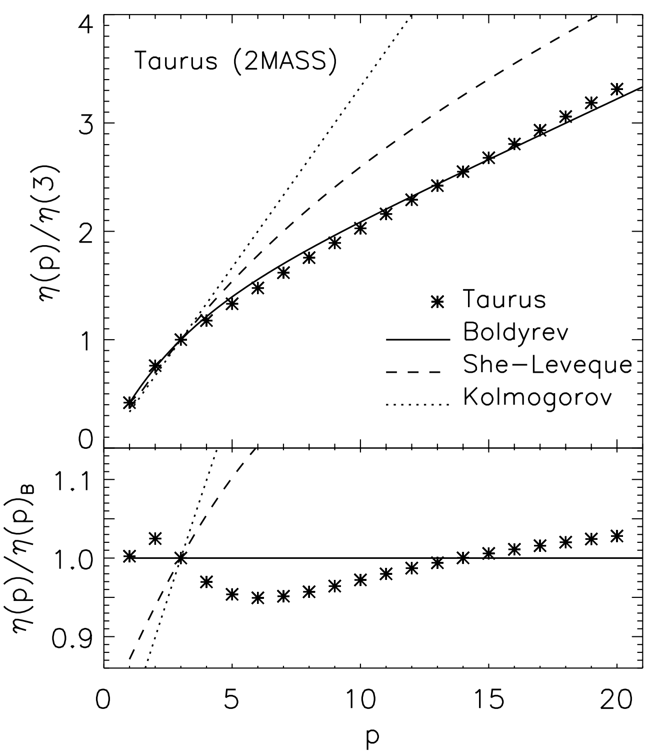
Taurus (2MASS)
Taurus
Boldyrev
She–Leveque
Kolmogorov
η(p)/η(3)
η(p)/η(p)B
p
0
1
2
3
4
0.9
1.0
1.1
0
5
10
15
20

Fig. 3.—